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## VLBI Techniques in Pulsar Astronomy

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**Abstract.** Very long baseline interferometry (VLBI) provides the resolution needed to make precision measurements of a pulsar's parallax and proper motion. In making these measurements, the astronomer is faced with difficult calibration problems and a paucity of strong point-like calibrators that ultimately limit the accuracy of parallax measurements of even the brightest pulsars. A new technique to calibrate away the effects of the ionosphere, the dominant source of phase error at frequencies below 5 GHz, has led to the new measurements of nine pulsar parallaxes to 100 microarcsecond or better precision.

### 1. Introduction

The case for measuring pulsar parallaxes is strong – many models based on other measurements of pulsars require estimates of the distances to the pulsars in the sample. Applications of pulsar distances are not within the scope of this paper as they are discussed in detail by Chatterjee in the following paper. This paper concentrates on making useful measurements of pulsars with VLBI and focuses mainly on high-precision astrometry.

### 2. VLBI

Interferometry is the radio astronomers answer to the optical astronomer's resolution. Building large single centimeter-wave telescopes with resolutions that come close to those of large optical telescopes is impossible. At 1.5 GHz, the dish would need to be 20 km in diameter – quite a mechanical feat. Even if such a marvel could be constructed, the ionosphere and troposphere could not be expected to be coherent over the entirety of the aperture. Fortunately phase-preserving amplifiers and stable electronics are available in the gigaHertz frequencies which allow the electrical combination of signals from many small antennas. Also important is that the radio photons are in the classical regime with occupation numbers much greater than unity, which allows amplification and duplication of the signals without a large sensitivity penalty. Once one can combine the signals from many small antennas, one can use aperture synthesis to probe features smaller than a milliarcsecond.

VLBI is probably best distinguished from connected-element interferometry by its scale – thousands of kilometers, typically. The distance and geographic barriers require the sampled electric field measurements to be recorded onto

(usually magnetic) media to be shipped from the antennas to a central correlator and the use different clocks at each station which must be stable and synchronized to better than microsecond precision. It also requires use of very detailed correlator models, especially for astrometric projects. These models include effects such as bending of light around the sun and Jupiter, tidal deformation of the earth, excursions from Earth's average spin, and plate tectonic motion. This model is used to calculate, to 10 ps or better accuracy, the expected geometric delay between the arrivals of the radiation from an astronomical source at the antennas. The input parameters to the model include station positions, the time of the observation, and coordinates of the source being observed (the phase center). The data products of the correlator are the cross-correlations of the signals from each pair of stations after taking into account the modeled delay. These are called visibilities.

### 3. Scattering

This paper will not focus on scattering, however for completeness I include a brief discussion. VLBI with its high angular resolution can measure the scattering disc size, constraining the distribution of scattering material along the line of sight to the source. Scattering increases strongly (as  $\lambda^2$ ) with wavelength.

While an image that exhibits the scattering disc can be reconstructed with the set of visibilities measured for a source, a more accurate measurement can be made by modeling the visibilities directly. The amplitude of a visibility is the flux density of the source being observed multiplied by the correlation coefficient, which for a point source would be unity. Earth rotation causes the projected antenna separations (baseline lengths) to change, probing a wide range of baselines. A detection of a scattering disc manifests itself as a drop in the correlation coefficient as a function of baseline length. The scattering-based decorrelation phenomenon can be useful for probing the ISM, but is generally a nuisance for VLBI at low frequencies as it reduces the effective resolution.

### 4. VLBI astrometry

Astrometry is the science of making precision measurements of positions of astronomical sources. Multi-epoch astrometry leads to measurements of proper motions and perhaps parallaxes. The phases of the complex visibilities contain astrometric information. In the absence of correlator model errors or other deviations from perfect calibration, the visibility phase for a point source is given by

$$\phi(\nu) = \frac{\nu}{c} (ul + vm), \quad (1)$$

where  $c$  is the speed of light,  $\nu$  is the observing frequency,  $(u, v)$  is the projected baseline vector, and  $(l, m)$  is the displacement vector of the source relative to the correlator model phase center. For a source that is exactly at the correlator phase center, this phase is zero. With multiple measurements of  $\phi$  made with different projected baselines,  $(u, v)$ , the source position,  $(l, m)$ , can be obtained.

Pulsar VLBI measurements are made almost exclusively in the 20 cm observing band. Pulsars have steep spectral indexes, making observing at higher

frequencies more difficult. The ionosphere, scattering, interference, and lower angular resolution all contrive to make observing at frequencies below 1 GHz difficult. Pulsar gating is often employed to improve the signal-to-noise of the pulsar measurements. Gating disables accumulation in the correlator during a pulsar's off-pulse phase.

#### 4.1. Phase-referencing

The ionosphere, just like the ISM, contains a non-homogeneous distribution of electrons which impart a dispersive delay to the incoming radiation. The ionosphere above each station can change substantially on timescales less than 1 minute, causing the relative phases to change, corrupting the astrometry. The bulk of this can be removed by a technique known as phase-referencing (Shapiro et al. 1979). In this process, a nearby point-like calibrator source with a well known position is observed alternately with the target with a cycle time of 2 to 4 minutes. Since the calibrator's position is well known, its visibility phases can be assumed to be purely due to calibration problems. These phases are then interpolated across the pulsar's observation and subtracted from the pulsar's corresponding visibility phases. This standard observing technique calibrates away most of the ionosphere's effect, but the uncorrected ionosphere gradients often leave significant and systematic phase errors.

#### 4.2. Ionospheric calibration

After phase-referencing at frequencies lower than about 5 GHz, the remaining phase errors are dominated by the effects of the ionosphere. The dispersive nature of the ionosphere can be exploited in its removal. The unwanted phase as a function of frequency for a given visibility can be expressed as

$$\phi^{\text{iono}}(\nu) = \frac{B}{\nu}, \quad (2)$$

where  $B$  is the strength of the uncalibrated ionosphere. The phase-referenced visibility phase then has the form

$$\phi^{\text{vis}}(\nu) = \frac{\nu}{c} (ul + vm) + \frac{B}{\nu}. \quad (3)$$

The difference in frequency dependence of the first, wanted term and the second, unwanted term make it possible to measure  $B$  and remove its effect from the visibility phase, allowing precise astrometry. Additional details of this technique and a discussion of its applicability can be found in Briskin et al. (2000 & 2002). A project to measure the parallaxes of 10 pulsars was started in 1999 after success of this technique was demonstrated on pulsar B0950+08 (Briskin et al. 2000). In this experiment, the NRAO<sup>1</sup> Very Long Baseline Array (VLBA) was used in the 1400–1730 MHz band. Eight frequency sub-bands, each 8 MHz wide, were placed across 330 MHz. Five epochs of observation were planned for each pulsar over the course of one year. One pulsar, J2145-0750, was not detected in either

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<sup>1</sup>The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

of its first two epochs and was subsequently abandoned. Successful parallax measurements were made for the nine remaining pulsars with a typical precision of 100 microarcseconds (Brisken et al. 2002). See Table 1 for the results.

### 4.3. In-beam calibration

A second method to improve phase-referencing is to use a phase-reference calibrator source that is very close to the target. In the case that a compact source of sufficient flux density (about 5 mJy for the VLBA) is within the same primary beam as the target (about 25 arcminutes for the VLBA at  $\lambda \sim 20$  cm), both can be observed simultaneously. At correlation time, each source is correlated separately with its own phase center. The simultaneous observation of the calibrator and target mean that no temporal interpolation is needed and the spatial proximity implies that ionospheric gradients contribute little to the phase-referenced visibility phase. Finding a suitable in-beam calibrator is often difficult or impossible. Once a good calibrator is found, a successful parallax measurement is almost guaranteed.

Table 1. Parallaxes of radio pulsars

Pulsar	$\pi$ (mas)	Technique <sup>†</sup>	Reference
B0329+54	$0.94 \pm 0.11$	Iono <sup>1</sup>	(1)
J0437–4715	$7.19 \pm 0.14$	Timing	(2)
B0809+74	$2.31 \pm 0.04$	Iono	(1)
B0823+26	$2.8 \pm 0.6$	Phase-Ref <sup>2</sup>	(3)
B0833–45	$3.4 \pm 0.7$	Optical (HST)	(4)
B0919+06	$0.83 \pm 0.13$	In-beam <sup>3</sup>	(5)
B0950+08	$3.81 \pm 0.07$	Iono	(1)
B1133+16	$2.80 \pm 0.16$	Iono	(1)
B1237+25	$1.16 \pm 0.08$	Iono	(1)
B1451–68	$2.2 \pm 0.3$	In-beam	(6)
B1534+12	$0.91 \pm 0.13$	Timing	(7)
J1713+0747	$0.9 \pm 0.3$	Timing	(8)
J1744–1134	$2.8 \pm 0.2$	Timing	(9)
B1855+09	$1.1 \pm 0.3$	Timing	(10)
B1929+10	$3.02 \pm 0.09$	Iono	(1)
B2016+28	$1.03 \pm 0.10$	Iono	(1)
B2020+28	$0.37 \pm 0.12$	Iono	(1)
B2021+51	$0.50 \pm 0.07$	Iono	(1)

<sup>†</sup> 1: see Sec. 4.2.; 2: see Sec. 4.1.; 3: see Sec. 4.3. References: (1) Brisken et al., 2002; (2) van Straten et al. 2001; (3) Gwinn et al., 1986; (4) Caraveo et al., 2001; (5) Chatterjee et al., 2001; (6) Bailes et al., 1990; (7) Stairs et al., 1999; (8) Camilo et al., 1994; (9) Toscano et al., 1999; (10) Kaspi et al., 1994.

### 4.4. Disc-based recording

VLBI has traditionally relied on large (in physical dimension and data capacity) magnetic tapes for storage and transportation of data from the antennas to

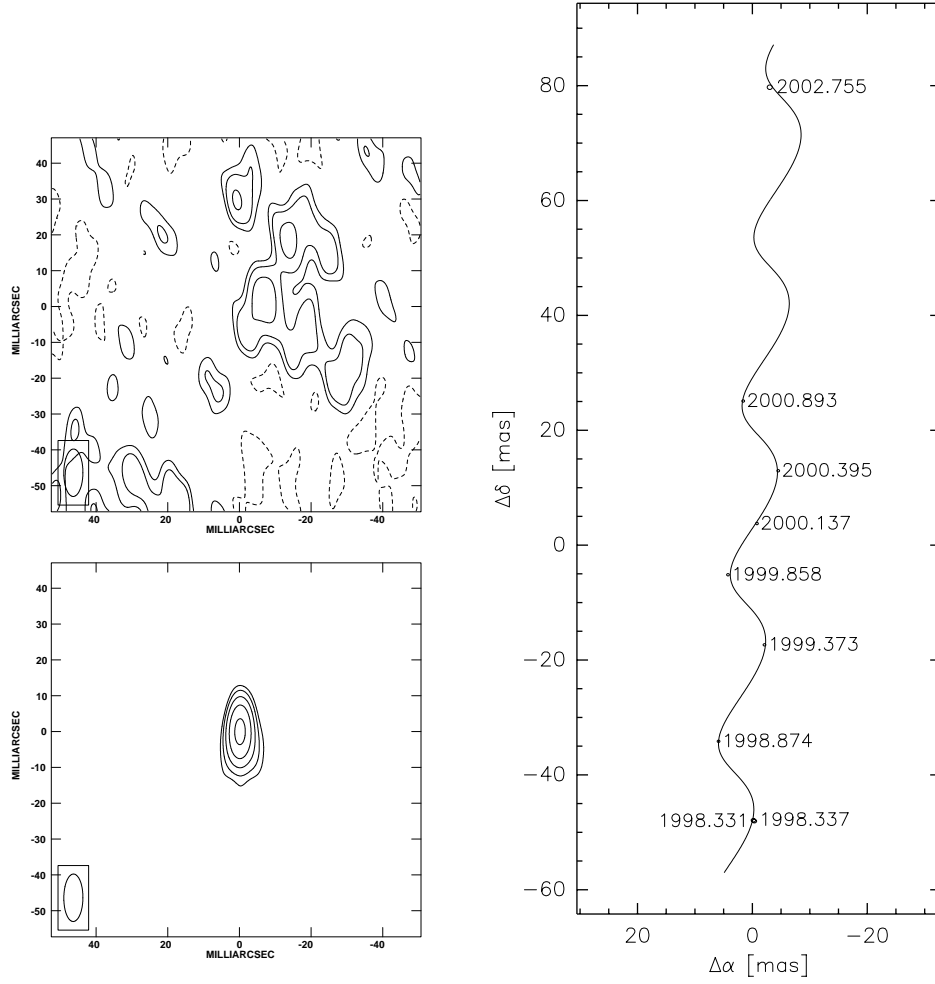


Figure 1. Ionospheric calibration applied to B0950+08. The top left figure is a contour plot showing the image made of B0950+08 prior to ionosphere calibration. The bottom left figure shows the same after ionosphere calibration. The lowest contour in each image is at 5 mJy beam<sup>-1</sup>. A factor of 2 separates consecutive contour levels. The beam size for each is 4 by 11 milliarcseconds. The right figure shows the best fit parallax ( $\pi = 3.81 \pm 0.07$  mas) and proper motion ( $\mu_\alpha = -2.06 \pm 0.06$  mas yr<sup>-1</sup>,  $\mu_\delta = 29.37 \pm 0.05$  mas yr<sup>-1</sup>). The data point from year 2002.755 used only 3 VLBA stations; the Mark 5 recording system was used at the Pie Town station. Note that the sizes of the ellipses near each date represent the positional uncertainty at that epoch.

the correlator. Market pressure over the last decade has forced the price of commodity IDE discs to fall below that of magnetic tape. Discs have additional benefits over tapes for reasons including: random access to data is possible, much less maintenance is required, recording rates can be greater and capacity scales with the consumer market. The pulsar community may greatly benefit from the deployment of disc-based VLBI recorders at most large radio telescopes in the near future.

Haystack Observatory is leading the Mark 5 disc-based recorder project. To date, roughly 20 prototype units are deployed. The VLBA achieved first fringes with its first Mark 5 prototype on 13 Oct. 2002. Pulsar B0950+08 and its phase reference calibrator were observed with magnetic tape at the St. Croix and Hancock, NH VLBA stations and onto a Mark 5 recorder at the Pie Town, NM VLBA station. This data point augments 8 previous epochs and is shown in Fig. 4.2.. The updated parallax for B0950+08 is shown in Table 1.

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